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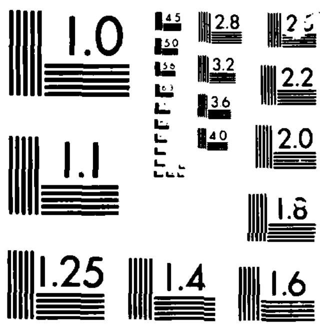

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AGARD ADVISORY REPORT No.222

TECHNICAL EVALUATION REPORT OF AGARD TECHNICAL MEETING ON UNSTEADY AERODYNAMICS – FUNDAMENTALS AND APPLICATIONS TO AIRCRAFT DYNAMICS

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AGARD Advisory Report No.222

TECHNICAL EVALUATION REPORT OF AGARD TECHNICAL MEETING ON UNSTEADY AERODYNAMICS — FUNDAMENTALS AND APPLICATIONS TO AIRCRAFT DYNAMICS

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TECHNICAL EVALUATION REPORT OF
AGARD TECHNICAL MEETING ON
UNSTEADY AERODYNAMICS-FUNDAMENTALS
AND APPLICATIONS TO AIRCRAFT DYNAMICS
(GOTTINGEN, GERMANY, MAY 6-9, 1985)

by

D. G. Mabey and J. R. Chambers

1. INTRODUCTION

From May 6-9, 1985, the Fluid Dynamics Panel and Flight Mechanics Panel of AGARD jointly arranged a Symposium on "Unsteady Aerodynamics-Fundamentals and Applications to Aircraft Dynamics" at the Stadthall, Gottingen, West Germany. This Symposium was organized by an international program committee chaired by Dr. K. J. Orlik-Ruckemann of the Fluid Dynamics Panel.

The program consisted of five sessions grouped in two parts:

I. Fundamentals of Unsteady Aerodynamics
II. Applications to Aircraft Dynamics

The 35 papers presented at the 4 day meeting are published in AGARD CP 386 and listed in the Appendix. As the papers are already available and cover a very wide field, the evaluators have offered brief comments on every paper, followed by an overall evaluation of the meeting, together with some general conclusions and recommendations. The views expressed are the sole responsibility of the evaluators.

The current interest in unsteady aerodynamics and the importance of its impact on aircraft dynamics are well illustrated by the record attendance of approximately 250 scientists at this Conference and by some recent AGARD publications[1-9]. These references provide a useful introduction to recent research in this rapidly developing subject.

2. REVIEW OF PAPERS

2.1 Fundamentals of Unsteady Aerodynamics

2.1.1 Unsteady separation and dynamic stall

LASCHKA presented an overview of the fundamental equations describing unsteady flows.[A1*] He illustrated how the types of solution obtained alter radically with changes in the boundary conditions of the problem. The usual viscous boundary conditions on a surface are zero slip and zero normal velocity. The effect of a downstream or upstream moving wall introduces singularities into the flow away from the wall. This concept was developed further in a subsequent paper.[A6] Laschka also stressed that the solution of the equations for a fixed point is always composed of a steady mean value, an organized fluctuating term and a turbulent, random-fluctuating term. It is often assumed by both experimental and theoretical aerodynamicists that because the second term is absent from their problem, the third term is zero. Even if the third term does exist, it is often regarded as being of no significance.

As an important example of this problem Laschka remarks that "The common understanding on separation in two dimensional steady flow over a wall at rest is based on Prandtl's concept of a boundary layer having vanishing wall shear." It is likely that steady separation never exists in turbulent flow - i.e., solutions of the Navier-Stokes equations with separation will always be unsteady and probably random in character.

CARTA presented a review of some preliminary dynamic stall experiments on 2-D 30° swept and unswept oscillating wings.[A2] Most of these measurements relate to tests of an NACA 0012 airfoil with free transition at a chordwise Reynolds number of about 2.8×10^6. Many of the anomalous results within the experiment could be explained if it is assumed that for 30° sweep, spanwise contamination makes the boundary layer turbulent. If this is correct, the failure to fix transition has caused the simultaneous variation of two parameters (transition condition and leading-edge flow). Conclusions based on the measurements are therefore somewhat tentative.

COUTANCEAU presented a comparison between a solution for the Navier-Stokes equations and an experiment for the flow over an NACA 0012 airfoil at 34° incidence at low Reynolds number (10^3). Excellent agreement between theory and experiment was obtained.[A3] In particular, the development of both a leading- and trailing-edge separation was delineated beautifully. Coutanceau doubted whether perfect fluid solutions (even with the unsteady Kutta condition satisfied both at the leading and trailing edge) would be adequate to model this problem.

DE RUYCK presented velocity and turbulence measurements on a stalled, oscillating NACA 0012 airfoil.[A4] Although the Reynolds number was low (only 0.3×10^6) a trip wire was provided to fix transition close to the leading edge. Both a leading-edge vortex and a trailing-edge separation are observed at different points in the cycle. Trailing-edge separation tends to be suppressed by an increase in frequency parameter as predicted by Geisler.[A7] A valuable addition to this paper would be provided by time-dependent pressure measurements.

*Refers to paper reference numbers in AGARD CP 386 as listed at the end of this report.

MARESCA presented measurements[A5] of steady and time-dependent forces on a fixed NACA 0012 airfoil with free transition at a low Reynolds number (0.1×10^6) at fixed incidences of ±6° and ±20°. The time dependence of the flow at the "receptor" airfoil was introduced by the longitudinal oscillation of another NACA 0012 airfoil two chords upstream. This "emittor" airfoil also had free transition and an incidence of 20°. The "emittor" airfoil produces alternately potential flow and flow with strong vorticity but it is difficult to be certain of flow conditions at the "receptor" airfoil or if the flow is two-dimensional.

ERICSSON presented a critical look at the dynamic simulation of viscous flow.[A6] The large and complicated static scale effects on NACA 0012 airfoils should deter experimenters from choosing this airfoil for basic research in time-dependent aerodynamics. The importance of the parameter $\dot{\alpha}\, c/U$ in time-dependent experiments was stressed. The concept of the moving leading edge is useful for modeling moving airfoil problems. The influence of wall interference (e.g., open, closed, or slotted walls, sidewall boundary layers) on dynamic simulation was raised in discussion. Apart from the European NORA tests (Ref. 9), no experiments or calculations are believed to have addressed this controversial question.

GEISSLER gave a lucid exposition of some new calculations of dynamic stall on NACA 0012 and Ames A01 airfoils.[A7] The inviscid flow is calculated by an incompressible panel method. The unsteady boundary-layer equations are solved by a time marching technique which always starts from the front stagnation point. The usual boundary-layer assumption of zero normal pressure gradient is retained. Although the boundary-layer calculations break down at the separation point, the results still look sensible. The boundary layer is assumed to be turbulent from the front stagnation point. This is a legitimate assumption because of the complexity of the flow with free transition. Good comparisons are obtained generally for both airfoils. In particular, increasing Reynolds number tends to suppress the trailing-edge separation. Similarly, for a given Reynolds number an increase in frequency parameter tends to suppress the separation. Geissler thought it would be relatively easy to modify the panel method to allow for compressible flow in the leading-edge region at high angles of incidence.

2.1.2 Unsteady boundary layers

CEBECI presented a comprehensive review paper mainly concerned with the prediction of unsteady turbulent boundary layers.[A8] An interesting conclusion is that (at least for attached time-dependent turbulent boundary layers) the algebraic viscosity formulation of Cebeci and Smith gives results identical with those of Bradshaw et al. No view is expressed in the paper whether this conclusion would be valid for flows which include separation. The transition position in quasi-steady flows is identical with that for steady flow whereas for oscillatory flows there are significant differences. Indirectly this observation re-inforces the desirability of controlling transition position in time-dependent experiments.

BRERETON gave some new results from the Stanford University Turbulent Boundary Layer Program.[A9] The water tunnel used has many interesting features. It is important to note the careful way the thin initial turbulent boundary layer is developed and how the sudden pressure gradients are varied. The main conclusion is that most of the boundary layer (the outer "wake" region) moves as a "plug" at free-stream velocity. The adverse pressure gradients were first increased to provoke separation and then reduced to re-establish attached flow. The steady separation bubble took much longer to develop than to blow away. This interesting observation is in accord with recent experiments on a rapidly moving spoiler (Ref. 12).

BINDER gave another set of unsteady turbulent boundary-layer measurements in a water tunnel,[A10] and these results complement those of Reference A9. The relevant frequency parameter is considered to be based on Stokes' length $\sqrt{2\nu/\omega}$ and the parameter u_τ/ν. The unsteady and steady velocity profiles are the same. Similarly, the steady and unsteady turbulent profiles are the same. This implies that the turbulent boundary layer in this experiment behaves as a quasi-steady flow.

COUSTEIX presented some unsteady turbulent boundary-layer measurements in a wind tunnel and a simplified theory based on an integral method.[A11] In this experiment the time dependence of the flow was produced by the rotation of a paddle wheel at the end of a diffuser. Cousteix suggests that for values of the parameter $\sqrt{2\nu/\omega} \times u_\tau/\nu$ less than 8, unsteady effects are confined to the viscous sublayer. This corresponds to higher values of circular frequency (ω) and could be an important limit in many paractical problems. The integral theory developed should be relatively easy to apply and is valid up to separation where a singularity develops. This theory could find application to a wide range of problems.

2.1.3 Unsteady airloads

MYKYTOW had the unenviable task of summarizing a previous SMP meeting on transonic unsteady aerodynamics.[A12] Some of the interesting papers discussed included the aerodynamic resonance observed in experiments on an oscillating airfoil with separated flow, and the first successful three-dimensional unsteady Euler calculations for transonic speeds by Salmond made for the AGARD SMP tailplane. In addition, Laurent had predicted Tijdeman type A, B, and C shock oscillations occurring simultaneously on a swept rectangular wing. Mykytow concluded that if such rapid progress is maintained, three-dimensional viscous flutter calculations will be possible in the next decade.

GOORJIAN presented some calculations related to a curious aeroelastic oscillation observed on the B-1 aircraft over a narrow range of flight conditions (e.g., Λ = [illegible], M = 0.873, α = 8.1° to 8.4°). Calculations presented suggest that for this condition no shocks are present on the wing.[A13] Thus the oscillations cannot be attributed to shock induced separation. The flight tests show that for M = [illegible], Λ = [illegible], the static trailing-edge pressure has diverged at 83% semi-span but not at 72% semi-span, consistent with this hypothesis. This oscillation represents a problem which would merit further investigation. One interesting suggestion made during discussion was that the oscillation was excited by an alternation in flow pattern from one vortex to two vortices.

HOUWINK presented results of some time-dependent calculations for oscillating airfoils with separated flow.[A14] The method uses a strong interaction between an inviscid transonic flow and a separated, quasi-steady turbulent boundary layer. It predicts the curious aerodynamic resonances on an oscillating airfoil cited by Mykytov (loc cit above) as well as the general shape of the boundary for a single degree-of-freedom flutter on a model of a swept wing. So far, attempts to predict separated periodic flows on rigid biconvex airfoils at transonic speeds by this method have been unsuccessful. However, these attempts are continuing.

BUERS presented a comparison between wind-tunnel and flight measurements on the Alpha jet transonic wing.[A15] The most interesting feature was the successful measurement in flight of unsteady pressures at a few typical positions on four spanwise sections. In addition, there were comparisons between the flight measurements and wind-tunnel tests on the identical aircraft wing at full-scale Reynolds number and a wind-tunnel test on a 1/10-scale model. There was large dynamic intereference in both sets of wind-tunnel tests on both the unsteady pressures and the model response due to the high level of flow unsteadiness in both facilities. The wind-tunnel tests of the full-scale wing were made with free transition. Most of the wind-tunnel tests on the 1/10-scale model were made with free transition at a Reynolds number of only 2.5×10^6. These tests with free transition agreed better with the flight measurements than the measurements with fixed transition, for which no attempt was made on the model wing chord to achieve the full-scale ratio of boundary-layer thickness/wing chord. Only a few flight tests achieved stable buffeting for 10 seconds (about 100 random cycles) and reliable total damping estimates were not extracted. Hence, the current requirement of calculating the buffet excitation parameter in every mode (Refs. 13 and 14) could not be achieved. The direct comparison between model and aircraft accelerations is totally misleading.

MEIER presented a comparison between calculated and measured interactions between either a single vortex, or a Karman vortex street, and a NACA 0012 airfoil with free transition.[A16] For a Mach number of M = 0.80 the Reynolds number was only about 0.5×10^6. The circulations of the single vortices and the Karman vortices were about 0.7Uc and 2.0Uc, respectively. This paper provoked an interesting discussion. When the vortex passes close to the airfoil it is apparently destroyed; if this occurred this would violate Kelvin's theorem.

BEDDOES presented a feasibility study to determine if realistic helicopter noise signatures could be predicted for the interaction of a rotor and its wake.[A17] This strip theory method is essentially subsonic in character, but should be valid up to M = 0.80. Although in certain flight conditions the rotor often cuts through the wake, for these calculations this displacement is limited to about 0.1c. This displacement is of the same order as in the two-dimensional tests of Reference A16. A direct comparison between the results of Reference A16 and Beddoes' calculations would be of interest.

2.2 Applications to Aircraft Dynamics

2.2.1 Determination of dynamic stability derivatives

MALCOLM summarized results obtained from two rotary-balances recently utilized for tests of an F-15 model in the NASA-Ames 12-Foot Pressure Tunnel and a Standard Dynamics Model in the Ames 6- by 6-Foot Supersonic Tunnel.[A18] The F-15 data displayed large effects of a nose boom at high-α, sting-support interference, and large nonlinearities with spin rate for angles of attack above 40°. The data also indicate significant aerodynamic hysteresis in yawing moment for a limited range of Reynolds number. Unfortunately, the test rig did not incorporate motion-picture or video monitoring concepts for flow visualization and correlation of physical flow state with the hysteresis effects was not achieved. Despite this shortcoming, the program represented a milestone event in improved test capability at high Reynolds numbers, and subsequent correlation of the F-15 data with sub-scale model flight results and follow-on experiments are anxiously awaited.

O'LEARY reported on tests of a three-surface High Incidence Research Model (HIRM) utilizing a new rotary rig at RAE, Bedford, including comparison of results with small amplitude oscillatory tests.[A19] The rig is relatively unsophisticated, and the manual adjustment of angle of attack and balance weights appear to be time intensive. The canard-configured HIRM model exhibited significant nonlinearities and asymmetries at high-α, and the effects of canard deflection on dynamic derivatives were large. Correlation of the rolling moment due to steady rolling agreed well with results of forced oscillation tests, although the technical accuracy of such comparisons was questioned in discussions. Again, unexplained nonlinear trends in aerodynamic behavior were not analyzed with flow visualization.

JANSSON described the updated subsonic and transonic dynamic derivative capability at FFA in the L2, S4, and HT tunnels. Pitch-yaw, rotary balance, and semi-span oscillating rigs were described and results obtained from tests of the Standard Dynamic Model were discussed.[A20] Configuration tests included the effects of inlet condition and asymmetric wing-body strake on conventional and cross-coupling derivatives. A control surface oscillation apparatus for measurement of control derivatives was also discussed, and interesting results showing the effect of angle of attack on dynamic canard control effectiveness were presented. Discussion of the paper centered on the mechanical difficulties and data reduction problems encountered in check-out of the rigs, particularly due to rearward-mounted torque gages.

SCHMIDT presented extensive data for the Standard Dynamics Model (SDM) as measured with the DFVLR/AVA transonic derivative balance.[A21] The test apparatus, known as Transonic AVA Derivative Rig (TRAD) was employed for pitch, roll, and yaw tests of the SDM.Data trends were extremely nonlinear, even at moderate angles of attack, suggestive of major interference effects and/or flow separation. Correlation with similar data for the SDM measured at FFA and AEDC was generally good; however, as observed by the author, the aerodynamics of the SDM configuration are extremely sensitive and less than desirable for check-out of new balance systems.

RENIER presented an extremely interesting review of unconventional rotary balance testing at ONERA-IMFL directed toward identification of aerodynamic characteristics.[A22] Topics included simulation of motions wherein the velocity vector and rotational vector are not coincident, and dynamic stall effects observed during continuous rotations. This paper illustrated the significant advances made in the application of the relatively new test apparatus at Lille. The identification of $\dot{\beta}$ derivatives and other unsteady effects known to be important for high-α conditions stimulated the audience, many of whom requested additional information on this fine work. It is very desirable at this time to encourage the exchange of AGARD information on rotary testing, possibly by a Panel Working Group.

KRAG reported on tests conducted in the MUB Subsonic Wind Tunnel during 1981 at DFVLR Braunschweig to define the characteristics of four different types of gust generators.[A23] Detailed surveys of test section flow qualities were presented for mechanical and jet-flap gust generation concepts as well as sidewall-mounted low-aspect-ratio winglets. Various aspects of the test variables were discussesd, including the effects of wall interferences, slotted tunnel walls, and longitudinal gust components. Although the test instrumentation and results were relatively extensive, the paper was criticized during discussion as contributing nothing new to the technology of tunnel gust generation systems, many of which have been in operation for many years.

ILIFF presented an overview and tutorial of the maximum likelihood estimation concept of extraction of stability and control derivatives from flight data.[A24] The impact of flight at extreme conditions (such as high angles of attack) on various aspects of mathematical modeling, definition of mass characteristics, piloting maneuvers, and instrumentation and sensors was reviewed, and the essential characteristics of the maximum likelihood estimation technique were described using a simple example. The example showed the value of low measurement noise, multiple estimates at a given flight condition, and Cramer-Rao bounds. The paper presented a confident perspective of the ability of the analyst to define complex aerodynamic phenomena from flight data; however, the author emphasized the need for more definitive wind-tunnel data for characterization of high-α data.

2.2.2 Prediction of aircraft responses

TOBAK presented an excellent paper on the rapidly-growing application of bifurcation theories to nonlinear aerodynamic problems.[A25] He concentrated on the role of bifurcation theory in the modeling of aerodynamic phenomena classified as: linear or nonlinear single valued functions (typical aerodynamic behavior); multivalued functions (hysteresis); Hopf bifurcation (airfoil stall); strange attractor (forebody flow); and rate dependent functions (dynamic stall). The central theme of the paper was the importance of linking advanced modeling techniques, including aerodynamic bifurcation, with studies of nonlinear flight dynamics. Thus, the growing flexibility of the dynamicist to represent the complex aerodynamic behavior of vehicles at high angles of attack is rapidly maturing. The promise of these concepts, however, cannot be achieved without appropriate studies of fundamental aerodynamics to fully understand and characterize the phenomena which we are attempting to model.

HUI discussed how bifurcation theory can be used to study nonlinear dynamic stability characteristics.[A26] When the bifurcation parameter (such as angle of attack) is increased beyond a critical value, the steady motion loses stability, resulting in a finite-amplitude periodic motion. Applications of bifurcation concepts to a pitching airfoil in supersonic/hypersonic flow, flap oscillations in transonic flow, and wing rock of a slender delta wing in subsonic flow were discussed. Although the discussion centered on single-degree-of freedom examples, the author stressed the generalization of the technique to multi degrees of freedom, with the potential for chaotic behavior after a finite number of successive bifurcations. Several attendees asked about plans for additional applications of the technique to problems such as those involving static hysteresis with stable damping.

HANFF addressed the problem of representing aerodynamic loads under extreme flight conditions where highly non-linear phenomena exist, especially flight at high angles of attack.[A27] The author proposed an empirical representation of nonlinearities, including the use of a "reaction hypersurface," that defines the aerodynamic reaction in terms of motion variables. A wind-tunnel technique and data reduction system for the determination of the required data were also discussed. Representations of the reaction surface for linear and nonlinear single degree-of-freedom cases of roll motion and extrapolation of the method to multi degrees of freedom were illustrated. The method required no assumptions of linearity, and can be used to identify and analyze specific aerodynamic models. The concept does, however, require an extremely large and complete data base, including dynamic effects. The author claimed that the efficiency of the proposed wind-tunnel test method reduces the requirement to a manageable situation.

NGUYEN presented highlights of recent dynamic wind-tunnel experiments with the X-29 forward-swept wing demonstrator configuration.[A28] In these tests, unexpected large-amplitude wing-rocking motions and tumbling (autorotation) in pitch were observed during free-flight model tests. The wing-rock motions were caused by aerodynamic interference between the separated forebody vortical flow and the fuselage/vertical-tail combination. The motions could be damped by artificial roll rate damping supplied by wing-mounted elevons. The discussion emphasized the significant interference effects which occur for contemporary close-coupled aircraft, and the extremely complex nature of unsteady phenomena at high angles of attack. The tumbling characteristic resulted from the very large amount of negative static margin (over negative 30%) incorporated by the X-29 design. An analysis of the dynamic motions and aerodynamic characteristics of the configuration over an angle-of-attack range of ±180° was presented. At this point, the limited flight envelope of the X-29 airplane has prevented any attempt at correlation with flight.

LANG presented a very provocative and stimulating paper dealing with the anticipated operational need for "supermaneuverability" for future fighters and the potential significance of unsteady aerodynamics in achieving that goal.[A29] The expected lethality of future missile systems requires an increase in dynamic maneuvering performance, including the ability to rapidly "point" the airplane, change maneuver states more rapidly, and obtain rapid weapons delivery. The exploitation of dynamic aerodynamic effects, such as increased lift obtained during rapid dynamic stall maneuvers, might play a key role in this requirement. The author presented several examples of dynamic stall phenomena and potential concepts for dynamic flow control. The paper drew extensive discussion from the attendees, some of whom were doubtful that dynamic stall could significantly impact combat maneuvers due to the rapid reduction in dynamic lift effects. Also, the relative magnitude of dynamic lift was questioned for highly-swept configurations.

HANCOCK presented a fundamental review of some of the elementary ideas regarding the interactions between unsteady aerodynamics, dynamics, and control analysis.[A30] He presented a mathematical analysis of the single-degree-of freedom pitching motions of fixed-wing aircraft. The discussion centered on the representation of linearized unsteady aerodynamics and its interface with dynamic response. Particular attention was given to the derivative $C_{m_{\dot{\alpha}}}$.

ROSS reported on the correlation of predicted and free-flight behavior of a high incidence research model (HIRM) configuration.[A31] This RAE project utilizes several wind-tunnel and helicopter-drop models of a generic 3-surface fighter to advance the state of the art in departure/high-α prediction methods. The wind-tunnel tests included conventional static tests, oscillatory rig tests, and steady rolling tests. Drop model tests have been conducted in England as well as at the NASA Ames/Dryden Facility. Values of some derivatives had to be changed from wind-tunnel derived data in order to match the flight data. Analysis is underway to extract aerodynamic coefficients from flight data, and to design an automatic departure prevention system for future tests.

LAN discussed the results of a study to develop computational methods to predict wing rock for a high-aspect-ratio general aviation canard configuration and for a low-aspect-ratio fighter.[A32] A prediction method consisting of a lifting-surface method coupled with nonlinear airfoil section data was used to predict both static and dynamic lateral-directional derivatives. The results indicated relatively good correlation of predicted aerodynamics with wind-tunnel results, and when these data were used in equations of motion, good correlation with flight was shown.

VAN DER VAART presented results of a theoretical study of the effects of unsteady aerodynamics on symmetric aircraft responses due to elevator and vertical turbulence inputs.[A33] Calculations were made for the DeHavilland DHC-2, Fokker F27, and Boeing 747.

EVANS presented a paper dealing with the design of a self-organizing flight control system to suppress unacceptable trends in the longitudinal aerodynamics of a ground attack aircraft.[A34] The specific problem considered was a loss of pitch stability at high angles of attack.

CAVATORTA reported on the design of a gust alleviation system for a preliminary configuration of a commuter airplane.[A35] The analysis included aeroelastic effects, unsteady aerodynamics, mechanical nonlinearities, control surface rates, and deflection limitations. The results showed that the ride comfort could be improved by a least 50%.

3. TECHNICAL EVALUATION

Our overall impression is that since previous meetings, progress in the fundamentals of unsteady aerodynamics (section 2.1) has been relatively slow, whereas progress in the determination of dynamic stability parameters and their application to aircraft dynamics (section 2.2) has been relatively fast. The reasons leading to these differing assessments on the different parts of the meeting are now given.

3.1 Fundamentals of Unsteady Aerodynamics

Progress in unsteady aerodynamics is conveniently summarized under the two heads of theory and experiment. The attached flow theories presented were generally extensions of previous work, rather than interesting new concepts. Listening to many of the presentations it was possible to feel that the physics of the problem had got lost somewhere in the computer. This impression was especially true for the papers dealing with transonic flow, when the differing types of shock motion (Tijdeman Types A, B and C, Ref. 15) were never mentioned. This is a serious omission: these shock motions determine the character of the transonic flow and the extent of the non-linearity. More explicitly, every transonic theory should first demonstrate its ability to predict these differing types of shock motions. Then all solutions subsequently computed should be classified accordingly. This will admittedly be difficult for three-dimensional wings but has already been done for a swept wing by Laurent, as Mykytov reminded the meeting.

The unsteady theories for separated flow included new material and were therefore more interesting. Geissler's weak interaction theory (between an incompressible inviscid flow and an incompressible boundary layer) successfully predicted the general character of oscillatory trailing-edge stall at low speeds. Houwink's strong interaction theory (between a compressible inviscid flow and a compressible boundary layer) successfully predicted the general character of the aerodynamic resonance of an airfoil oscillating with shock-induced transonic flow. So far this method has not succeeded in predicting periodic shock movements due to separation on a rigid 14% thick biconvex airfoil. In contrast, LeBalleurs' strong interaction theory (Ref. 16) has succeeded in predicting the approximate Mach number range for this periodic flow, but with a frequency parameter much lower than that predicted by the thin layer - Navier-Stokes solution of Levy (Ref. 17) or experiments. The successful prediction of periodic flow on 14% thick biconvex airfoils (with fixed transition) is an essential bench mark test for all time-dependent transonic viscous flow theories (Fig. 1). The problem in well posed, has been reproduced over a wide range of Reynolds numbers and is insensitive to wall interference (Refs. 18 and 19).

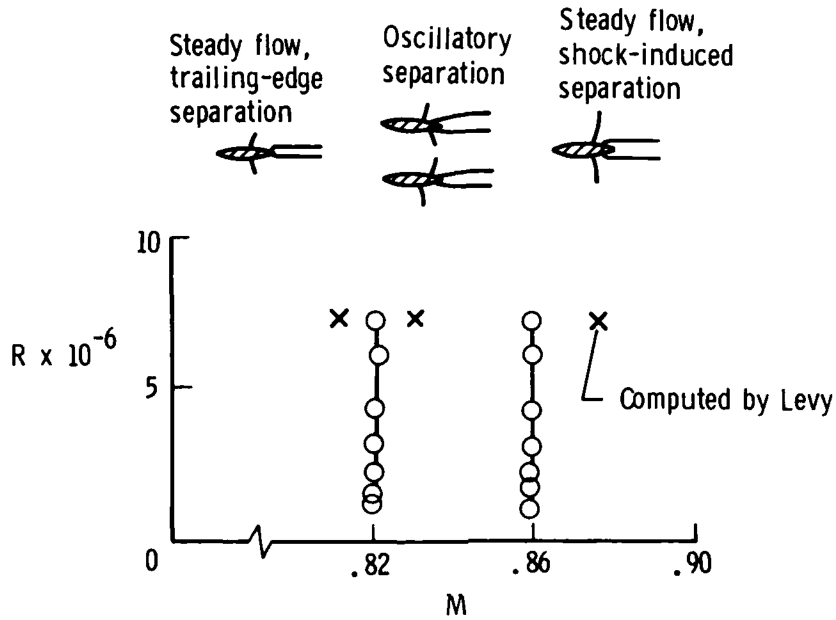


Figure 1.- Flow domains for a 14% thick biconvex airfoil. $\alpha = 0°$ (fixed transition).

Turning to the experiments in unsteady aerodynamics, a high proportion contained anomalous results because of a failure to fix transition. In many experiments transition was not fixed and an NACA 0012 airfoil was used at low Reynolds numbers. This airfoil is especially sensitive to variations in Reynolds number. Unsteady aerodynamics is a difficult subject, and we can ill afford to compound its complexity by effectively varying two parameters simultaneously. As a specific example, failure to fix transition probably determined the anomalous differences in the leading-edge region which were attributed to sweep in Ref. A2. A useful bench mark test, and a clear warning of the dangers of testing with free transition is again provided by the 14% thick biconvex airfoil. When tested with free transition the periodic flow disappears completely in the Reynolds number range from 2.5×10^6 to 5.5×10^6 (Fig. 2).

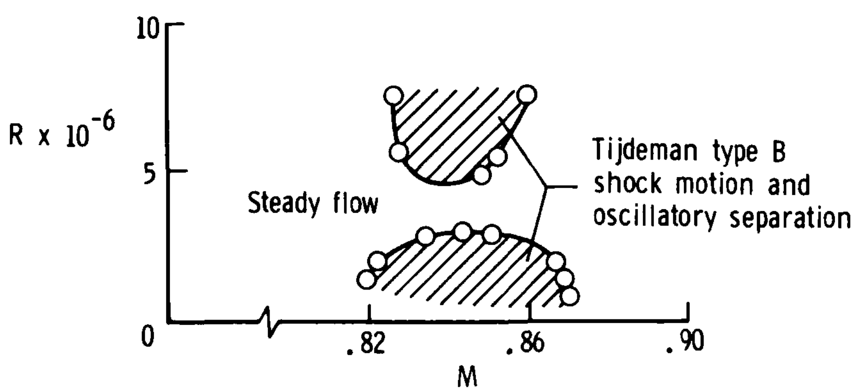


Figure 2.- Flow domains for 14% thick biconvex airfoil. $\alpha = 0°$ (free transition).

Many transonic tests are still made within this range. The implications of missing such an important phenomenon (present at full scale) in model tests with free transition are serious. For transonic speeds, it is not sufficient generally to fix transition close to the leading edge. Anomalous results will be obtained unless the correct ratio of boundary-layer thickness/local chord is reproduced at the shock. This is particularly true for supercritical wings, as illustrated by the anomalous buffeting measurements obtained with an arbitrary, fixed transition at a Reynolds number of 2.5×10^6 presented in Reference A15.

In contrast to the failure to fix transition in many of the unsteady experiments on airfoils or wings, it is significant that transition was fixed carefully in all three experiments on unsteady turbulent boundary layers.These experiments illustrated two important new features. Separation took a long time to develop but could be blown away quickly. For an attached boundary layer, only the wake region is influenced by the time-dependent free-stream flow. This experimental observation should encourage the use of quasi-steady turbulent shear layer models in time-dependent calculation methods.

Only one paper addressed the problem of wing buffeting (Ref. A15). The work was incomplete because the buffet excitation parameter $\sqrt{nG(n)}$, in the first wing bending mode (defined in Fig. 3(a) had not been derived from either the wind-tunnel or the flight tests. If this parameter had been derived, these measurements on a supercritical wing would have been a useful addition to other recent flight/tunnel comparisons (Refs. 13 and 14). These comparisons suggest that for the first wing bending mode a heavy buffeting limit is reached of about:

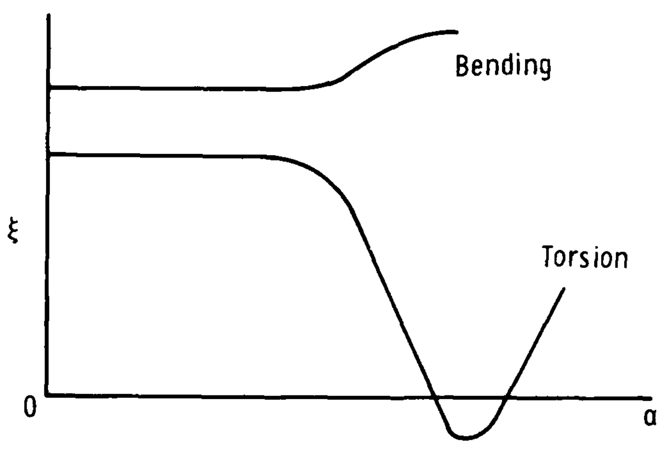
$$\sqrt{nG(n)} = 0.0030$$

irrespective of the type of wing planform and separation development. The physical reason behind

$$\sqrt{n\,G\,(n)} = \frac{2}{\sqrt{\pi}} \left[\frac{m\,y}{q\,s}\right] \xi^{1/2}$$

where m = generalized mass
y = wing tip rms acceleration
q = kinetic pressure
s = area
ξ = total damping in mode (fraction of critical)

(a) Equation



(b) Typical variation of total damping in two modes with angle of incidence

Figure 3.- Derivation of buffet excitation parameter.

the existence of this common limit would be a useful topic for further research. It is often forgotten that significant variations in aerodynamic damping occur on wings in separated flow (as sketched in some typical examples in Fig. 3(b). Such variations can be extrapolated from model to full scale (Refs. 13 and 14) so that full-scale flight responses can be calculated from wind-tunnel measurements of the buffet excitation parameter. In contrast, when unsteady pressures are measured at model scale, they can be integrated in time and space to give the approximate buffet excitation parameter, but they cannot give the aerodynamic damping. Extrapolation from model to full scale then rests on the dubious assumption that the aerodynamic damping in the separated flow region is the same as with attached flow.

No papers were presented on the application of cryogenic tunnels to unsteady aerodynamic tests: this omission should be rectified at the next meeting. Cryogenic tunnels achieve high Reynolds numbers (often full-scale values) by a combination of high density and low viscosity, despite a low velocity. The low velocity will make it easier to achieve high frequency parameters without prohibitively large aeroelastic responses which are always a problem in a conventional wind tunnel. For any random response to a constant level of the buffet excitation parameter, $\sqrt{nG(n)}$, (due either to flow unsteadiness in the tunnel or aerodynamic excitation due to separated flow on the model) it can be shown (Ref. 20) that if aerodynamic damping predominates

$$y \alpha R^{-1/5}$$

This relation (sketched in Fig. 4(a)) follows from the constant forcing $\sqrt{nG(n)} \times q$ and the increase

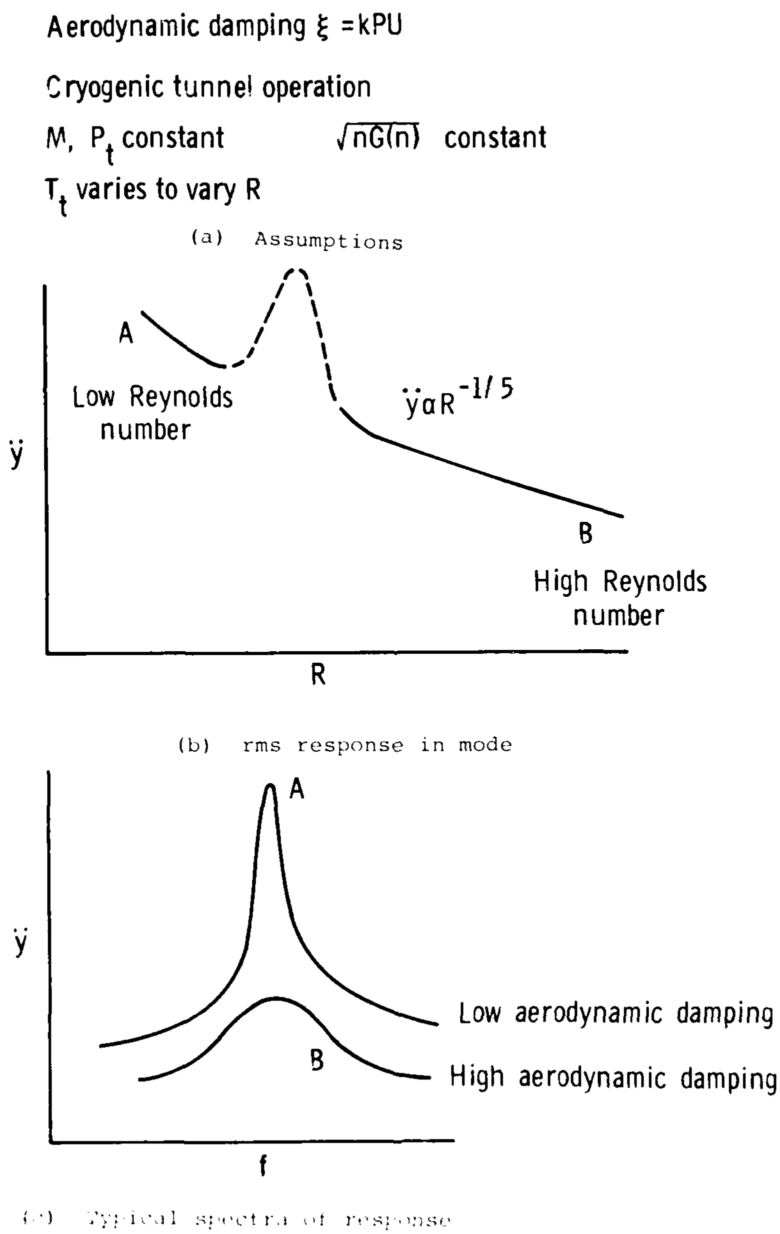


Figure 4.- Dynamic response to excitation in cryogenic tunnel.

in aerodynamic damping ζ as Reynolds number increases. It offers a simple explanation for the radically different character of the response at two total temperatures (i.e., two different Reynolds numbers) shown in a recent paper (Ref. 21, Fig. 10). Several low-speed cryogenic wind tunnels are now operational and it would be interesting to confirm that dynamic responses in these facilities satisfy the equation given above.

The introductory paper of the conference raised three important issues which were not addressed during the subsequent meeting and yet deserve attention in the future.

Any time-dependent measurement is composed of a mean value, an organized time-dependent and a random time-dependent term. Although the prediction of both steady and time-dependent separated flows were discussed, no attempt was made to predict the corresponding statistical properties of random terms caused by flow separations. Similarly, many results of dynamic airfoil tests were presented: these comprised the static characteristics and the corresponding organized time-dependent terms associated with the airfoil motion. Yet, no random unsteady forces generated by separation on rigid airfoils were presented for the same range of static conditions. Often this information could have deepened the understanding of results from oscillatory airfoil tests. Measurements of random quantities (e.g., pressures or forces) can be obtained generally without any additional instrumentation. Although perhaps minor changes may be necessary in the data acquisition system to obtain these random measurements, this is a small price to pay to achieve a complete description of the time dependent measurement.

Prandtl introduced the concept of steady flow separation (see discussion of Ref. A1, Fig. 10). However, it is doubtful if turbulent separation is ever steady. Thus, even when the free stream velocity has no organized time-dependent component, there will be random fluctuations in separation position and associated random pressure fluctuations near the mean separation point. If the separated shear layer reattaches to form a bubble, there is a local peak in the random pressure fluctuations which is a universal feature of all experiments. This peak in the random pressure fluctuations should be predictable by any fully comprehensive method for separated turbulent flow. Such calculations were not, in fact, presented at the conference.

The type of solution to time-dependent problems is sensitive generally to the precise nature of the boundary conditions. Thus, for separation from a moving wall the type of singularity is sensitive to the direction of movement (Ref. A1). No modification of surface boundary condition was discussed in this conference - apart from one comparative test with fixed and free transition (Ref. A15). One new type of boundary condition of current interest is the investigation of a shock-induced separation over a perforated surface which covers a shallow plenum chamber (e.g., Refs. 22 and 23) and others should be reported shortly. Another boundary condition of interest is the unsteady Kutta condition at the trailing edge in both attached and separated flows. A few years ago there was evidence (Ref. 24) that for transonic attached flow, random perturbations propagated upstream from the trailing edge to the shock, consistent with theory. However, for transonic separated flow, random perturbations apparently propagated predominately downstream from the shock to the trailing edge. What causes this change, and what happens to the direction of propagation in separated flow when the airfoil is oscillated at discrete frequencies? The answer to this question must be of direct relevance to computational fluid dynamics.

Another problem sensitive to the boundary condition is that of dynamic wall interference in wind-tunnel tests. Although no paper addressed this question, one offered a significant pointer. The gust generator (Ref. A23) produced quite different frequency responses in the working section depending on the wall boundary condition. Thus, the open tunnel had a completely different response from the slotted, partially slotted or closed working sections at all frequencies. In marked contrast the slotted, partially slotted and closed walls gave essentially the same response above a certain frequency limit. A tentative conclusion is that these walls should be preferred for tests at high frequencies because for them the precise boundary condition is not important. The significant response at zero frequency is due to tunnel unsteadiness and increases in the usual way (Ref. 25) from closed, to partially slotted, to slotted. The response is highest in the open jet section because of mixing at the boundaries and the end of the working section. Open jet working sections are widely used for gust research and other time-dependent experiments, often because of the ease with which models can be adjusted. Most of these advantages could be retained if the open jet walls were replaced by hybrid slotted walls. Hybrid slotted walls greatly reduce the level of flow unsteadiness (Ref. 25) and can be selected to minimize dynamic interference (Refs. 26 and 27).

3.2 Applications to Aircraft Dynamics

An honest assessment of the relative importance of unsteady aerodynamics to aircraft dynamics would indicate that, with the exception of classic aeroelasticity and flutter, relatively little interest has been shown by aircraft design teams in the recent past. Estimates of dynamic stability parameters, for example, were regarded as text book material for attached flow conditions and the aircraft industry has not significantly invested in research or facilities for this subject. Numerous aircraft programs have been successfully implemented under this philosophy. The increased stimulation and apparent progress in applications of unsteady aerodynamics to problems in aircraft dynamics is directly attributable to increased demands for maneuverability for combat aircraft. Current and future requirements for agility, relaxed stability, flight at high angles of attack with separated flows, and use of unconventional, closely-coupled canard configurations dominated by intense vortex flows represent challenges beyond the state of the art of current design methodology. In fact, the designer of future fighters must accurately predict and exploit ill-behaved, complex unsteady aerodynamics which were previously avoided by envelope limiting concepts or dismissed as relatively unimportant to flight dynamics. The increased emphasis on agility also results in rapid, large-amplitude motions which elevate the relative importance of unsteady effects to a level where certain phenomena, such as dynamic stall, may dictate the mission suitability of the vehicle. The large number of papers presented dealing with high-α conditions exemplify the fact that the challenge is recognized and being pursued by virtually every NATO nation.

Significant advances have been made, especially in the areas of new wind-tunnel test concepts and nonlinear analysis methods. However, the troublesome perspective exists that the technical community lacks a clear vision of the fundamental flow mechanisms and relative importance associated with many unsteady flow phenomena. For example, during the course of the conference numerous theories were advanced regarding the physical causes, modeling, and analysis of wing rock, the nature and relevance of hysteresis, and the existence and utility of dynamic stall for highly-swept fighters. Various views were espoused by relative factions within the extremely diverse conference attendees; however, none of the papers defined a study (or even a plan) which would coordinate the required efforts in flow diagnostics, experimental aerodynamics, and computational studies needed to provide <u>flight validated</u>, <u>relevant technology</u>. This shortcoming represents a major roadblock which will seriously inhibit programs in unsteady aerodynamics.

The papers dealing with the development of new wind-tunnel techniques for the determination of dynamic stability parameters convey highly successful efforts which have resulted in unprecedented test ability across a broad range of Reynolds number and Mach number. The majority of papers dealt with the development of mechanical rigs and data reduction systems with minimal discussion of applications. Although the use of generic models, such as the Standard Dynamics Model, is highly desirable for correlation of test installations and assessments of interference effects, it is also important to establish wind-tunnel/flight correlation for specific aircraft for high-α conditions. Innovative testing techniques, such as the non-coincident rotary tests discussed by Renier, offer revolutionary insight into unsteady derivatives which should be encouraged and accelerated.

The general approach and applications discussed in the sessions dealing with nonlinear aerodynamic representation and bifurcation theories were extremely encouraging. For several years, these potentially powerful analysis methods have been proposed for applications to high-α stability analysis, and the progress discussed by Tobak, Hui and Hanff offers optimism that this important area is now coming into focus on significant problems. The necessary close cooperation of the flight dynamicist and fluid dynamicist in the development and continued refinement of these techniques cannot be overstated.

Perhaps the most significant papers on applications to aircraft dynamics were those by Nguyen and Lang, wherein the importance of such parameters for highly agile future fighters was discussed and stressed. It is obvious that trends in fighter design demand an assessment of the impact of unsteady aerodynamics. Fighter agility has now increased to the extent that unsteady effects may become more important than classical static performance criteria. However, detailed information and a data base for representative values of Reynolds and Mach numbers is virtually nonexistent for realistic aircraft configurations. Major questions exist regarding the attainment and use of dynamic stall, vortex control and other dynamic flow control concepts. Providing this information will entail the use of wind tunnels, computational methods, and piloted simulated studies. It will be interesting to observe whether the technical community accepts this challenge. Much work is urgently needed across the spectrum of fluid and flight dynamics before the opportunities discussed by Lang will be seriously pursued by designers.

Several important contemporary problem areas relative to applications of unsteady flows to aircraft were not discussed at all in the conference. For example, the random, unsteady loads on twin vertical tails due to buffeting by vortex flows at high-α has become a major concern in fighter design. The prediction and alleviation of this phenomenon should be a major target of opportunity. Although mentioned by Lang, the concept of active control of unsteady aerodynamics for applications at high-α was not discussed; yet this concept may revolutionize the problems and solutions for aircraft design. Few solutions (either active or passive) for unsteady flow problems such as wing rock were discussed. As previously discussed, the lack of papers on flight validation of theory or ground test results was a serious omission.

Finally, the Technical Evaluators are highly appreciative of the fact that this symposium was organized as a joint effort of two separate AGARD Panels. Although this must have made the work of the program committee much more difficult, the resulting interaction of activities and interests of the aerospace communities involved, such as CFD, experimental aerodynamics, flight dynamics and system integration, was very important and most desirable. Such an interaction, to which the subject of unsteady aerodynamics is especially sensitive, is mandatory if any significant programs or breakthroughs in modern aircraft technology are to materialize. Although, in this age of specialization and compartmentalization, the required interplay of [illegible] was still difficult at this conference, it is only through initiatives like this one that the various groups of people will learn to communicate with each other and appreciate each other's problems and difficulties. AGARD's continuing efforts in this regard would be most valuable.

4. RECOMMENDATIONS

1. Wherever possible, the type of transonic shock motion should be identified in both theoretical studies and time-dependent experiments.

2. The Tijdeman type B shock motion observed on 14-percent thick biconvex airfoils should be used as a bench-mark test for all time-dependent transonic viscous-flow methods.

3. Transition should be fixed in all sub-scale time-dependent experiments. Initially wings and airfoils should be selected which are relatively insensitive to variations in Reynolds number.

4. For every buffeting test, the buffet excitation parameter should be calculated.

5. Some research should be initiated into the reasons behind the constancy of the buffet parameter at the heavy buffet limit for wings of widely varying planform.

6. More time-dependent tests should be made (with fixed transition) in small cryogenic tunnels to obtain dynamic measurements at high frequency parameters and high Reynolds numbers.

7. Whenever possible, time-dependent measurements should always comprise the mean value, the organized time variation and the random time variation.

8. The validity of Prandtl's concept of a steady separation should be investigated carefully for turbulent flow.

9. The effects of varying the time-dependent boundary conditions on a surface should be investigated.

10. More research is recommended into the difference between the dynamic trailing-edge condition for attached and separated flows at transonic speeds.

11. More research is needed into the effects of dynamic wall and support interference in wind-tunnel experiments.

12. Open-jet wind tunnels could be modified with advantage to hybrid slotted tunnels for time-dependent tests.

13. Oscillatory and Rotary-balance tests to obtain and analyze dynamic stability parameters should include flow visualization for identification of flow states, especially for conditions of aerodynamic hysteresis.

14. In view of the extensive experience gained in the last decade with rotary-balance test concepts within the AGARD community, the Fluid Dynamics Panel should sponsor a Working Group to document, correlate, and collate the test results.

15. The fundamental nature of dynamic stall effects for 3-D fighter-type configurations should be pursued in wind-tunnel tests, followed by piloted simulator studies to assess the effectiveness of dynamic lift in air combat scenarios.

16. A study should be undertaken of the effects of high oscillatory amplitudes and high-pitch ratios on the dynamic or transient behavior of aircraft. This is of particular interest for configurations expected to perform "supermaneuvers."

17. More research on the fundamental nature of complex separated flows (particularly at high angles of attack) is urgently needed to provide guidance on mathematical modeling and applications of advanced nonlinear motion analysis techniques, such as bifurcation theory.

18. The importance of unsteady aerodynamics and its impact on aircraft dynamics have been firmly established, especially as related to the increased demands for maneuverability for combat aircraft. The efforts in this field are gaining momentum in almost all NATO nations. Another review of the field in some 3 or 4 years would be most useful, perhaps in the form of a similar joint FDP/FMP Symposium.

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6. LIST OF PAPERS PRESENTED

A1. Unsteady Flows - Fundamentals and Applications (Invited Survey). B. Laschka, Technische Universität, Braunschweig, GE.

A2. Dynamic Stall of Swept and Unswept Oscillating Wings. F.O. Carta, United Technologies Research Center, US.

A3. Ecoulement Instationnaire Décollé d'un Fluide Incompressible Autour d'un Profil: Une Comparaison Theorie-Experience. O. Daube,; L.Ta Phuoc; Orsay Limsi; P. Monnet; M.Coutanceau, LMF, Université de Poitiers, FR.

A4. Velocity and Turbulence Measurements in Dynamically Stalled Boundary Layers on an Oscillating Airfoil. J. De Ruyck; C. Hirsch, Vrije Universiteit Brussel, BE.

A5. Profil d'aile en Décrochage Soumis à un Ecoulement Alternativement Potentiel et à Forte Vorticité. C. Maresca and D. P. Favier, Institute de Mécanique des Fluides de Marseille, FR.

A6. A Critical Look at Dynamic Simulation of Viscous Flow. L. Ericsson, Lockheed Missiles and Space Co., Inc., Sunnyvale, US.

A7. Unsteady Boundary-Layer Separation on Airfoils Performing Large Amplitude Oscillation - Dynamic Stall. W. Geissler, DVFLR - Göttingen, GE.

A8. Computational Aspects of Unsteady Boundary Layers. T. Cebeci, McDonnell Douglas Corporation, L. W. Carr, AVRADCOM, NASA Ames, A. A. Khattab; and S. M. Schimke, Douglas Aircraft Col, US.

A9. Dynamic Response to a Turbulent Boundary Layer to a Step Change in Free Stream Velocity. G. Brereton, W. C. Reynolds, Stanford Unviersity, L. W. Carr, AVRADCOM,NASA Ames, US.

A10. Etude Expérimentale de Couches Limites Turbulentes Instationnaires Soumises a des Gradients de Pression Moyens nuls ou Positifs. G. Binder, S. Tardu, J. L.Kueny, Institut de Mécanique de Grenoble,FR; and R. Blackwelder, University of Southern California, US.

A11. Couche Limite Turbulente Instationnaire: Investigations Experimentale et Numerique. J. Cousteix, and R. Houdeville, Complexe Aerospatial de Lespinet, Toulouse, FR.

A12. Review of SMP 1984 Symposium on Transonic Unsteady Aerodynamics and Its Aeroelastic Applications. W.Mykytow, AFWAL/FDL/FIBR, Ohio, US.

A13. Transonic Aerodynamic and Aeroelastic Characteristics of a Variable-Sweep Wing. P. M. Goorjian, NASA Ames Research Center; P. Guruswamy, Informatics General Corporation, Palo Alto; H. Ide, and G. Miller, Rockwell International, US.

A14. Unsteady Airload Computations for Airfoils Oscillating in Attached and Separated Compressible Flow. R. Houwink, National Aerospace Laboratory, NLR, NE.

A15. Wind-Tunnel and Flight Test Analysis and Evaluation of the Buffet Phenomena for the Alpha Jet Transonic Wing. H. Buers, Dornier GmbH, Friedrichschafen, GE, and V. Schmitt, ONERA,FR.

A16. Unsteady Interaction Between a Vortex and an Airfoil. G.E.A. Meier, and R.Timm, Max Planck Institute for Fluid Dynamics, Göttingen, GE.

A17. Unsteady Aerodynamics - Application to Helicopter Noise and Vibration Sources. T. S. Beddoes, Westland Helicopters Limited, Yeovil, Somerset, UK.

A18. Recent Developments in Rotary Balance Testing of Fighter Aricraft Configurations at NASA Ames Research Center. G. N. Malcolm, and L. B. Schiff, NASA Ames Research Center, US.

A19. New Rotary Rig at RAE and Experiments on a High Incidence Research Model (HIRM). C. O'Leary, and E. N. Rowthorn, Aerodynamics Department, RAE, Bedford, UK.

A20. New Dynamic Testing Techniques and Related Results at FFA. T. Jansson, and L. Torngren, FFA, Sweden.

A21. SDM Experiments with the DFVLR/AVA Transonic Derivative Balance. E. Schmidt, DFVLR, Göttingen, GE.

A22. Récents Développements des Techniques de Simulation Dynamique Appliquées a L' Identification des Paramètres de Stabilite. D. Tristant, and O. Renier, ONERA/Institut de Mécanique des Fluides de Lille, FR.

A23. Generation of 2D Gust Fields in Subsonic Wind Tunnels. B. Krag, and W. Wegener, DFVLR, Braunschweig, GE.

A24. Extraction of Aerodynamic Parameters for Aircraft at Extreme Flight Conditions. K. I. Iliff, NASA Dryden, US.

A25. Nonlinear Problems in Flight Dynamics Involving Aerodynamic Bifurcations. M. Tobak and G. Chapman, NASA Ames Research Center, US.

A26. Bifurcation Theory Applied to Aircraft Motions. W. H. Hui, University of Waterloo, Ontario, CA; and M. Tobak, NASA Ames Research Center, US.

A27. Dynamic Non-Linear Air Loads -Representation and Measurement. E. S. Hanff, NRC/NAE, Ottawa, CA.

A28. Recent Experiences of Unsteady Aerodynamic Effects on Aircraft Dynamics at High Angle of Attack. L. Nguyen, R. Whipple, and J. M. Brandon, NASA Langley Research Center, US.

A29. Unsteady Aerodynamics and Dynamic Aircraft Maneuverability. J. Lang, AFWAL/FIG, Wright-Patterson AFB, M.S. Francis, AFSC, US.

A30. On the Interface Between Unsteady Aerodynamics and Control. G. J. Hancock, and R. Vepa, Queen Mary College, University of London, UK.

A31. Correlation of Predicted and Free-Flight Responses Near Departure Conditions of a High Incidence Research Model. A. J. Ross, and G. F. Edwards, Aerodynamics Dept., RAE, Farnborough, UK.

A32. Theoretical Prediction of Wing Rocking. E. T. Lan, University of Kansas, US.

A33. Effects of Aerodynamic Lags on Aircraft Responses. J. V. Van Der Vaart, Delft, University of Technology, NE.

A34. A Self-Organizing Control System for Non-Linear Aircraft Dynamics. C. Evans, Smith Associates, Consulting System Engineers, Ltd., Cobham, Surrey, UK.

A35. Gust Alleviation on a Transport Airplane. E. Cavatorta, G. Caldarelli, Aeritalia spA, Naples IT, J. Becker, and F. Weiss, MBB, Munich, GE.

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14. Abstract

From May 6—9, 1985, the Fluid Dynamics Panel and Flight Mechanics Panel of AGARD jointly arranged a Symposium on "Unsteady Aerodynamics — Fundamentals and Applications to Aircraft Dynamics" at the Stadthall, Göttingen, West Germany. This Symposium was organized by an international program committee chaired by Dr K.J.Orlik-Ruckemann of the Fluid Dynamics Panel.

The program consisted of five sessions grouped in two parts:

I Fundamentals of Unsteady Aerodynamics
II Applications to Aircraft Dynamics

The 35 papers presented at the 4 day meeting are published in AGARD CP 386 and listed in the Appendix. As the papers are already available and cover a very wide field, the evaluators have offered brief comments on every paper, followed by an overall evaluation of the meeting, together with some general conclusions and recommendations.

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From May 6–9, 1985, the Fluid Dynamics Panel and Flight Mechanics Panel of AGARD jointly arranged a Symposium on "Unsteady Aerodynamics – Fundamentals and Applications to Aircraft Dynamics" at the Stadthall, Göttingen, West Germany. This Symposium was organized

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AGARD-AR-222

Aerodynamics
Aerodynamic stability
Aircraft
Unsteady flow

by an international program committee chaired by Dr K.J.Orlik-Ruckemann of the Fluid Dynamics Panel.

The program consisted of five sessions grouped in two parts:

I Fundamentals of Unsteady Aerodynamics
II Applications to Aircraft Dynamics

The 35 papers presented at the 4 day meeting are published in AGARD CP 386 and listed in the Appendix. As the papers are already available and cover a very wide field, the evaluators have offered brief comments on every paper, followed by an overall evaluation of the meeting, together with some general conclusions and recommendations.

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